

Variable Rates of Acceleration of the Greenland Ice Sheet Due to Penetration of Surface Meltwater

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Summer melt in the ablation zone of the Greenland Ice Sheet penetrates through ice 1 km thick, lubricating the bed and causing a summer speedup. Should continued warming reinforce this process, faster flow could cause drawdown of the ice sheet surface to lower, warmer elevations, providing a positive feedback. We compare subdaily ice velocity and uplift derived from nine global positioning system stations in the upper ablation zone in west Greenland to surface melt and supraglacial lake drainage during the summer of 2007. A speedup of over 30%, lasting approximately 40 days, occurred across the region. Sliding appears to be driven by diurnal and episodic pulses of meltwater delivery to the bed. The impact on velocity from surface melt decayed as the season progressed, indicating evolving efficiency of the subglacial hydrologic system. Thus, increases in seasonally averaged summer melting may not guarantee faster seasonal ice flow.

Fig. 1. Meltwater lake draining water to the bed of the Greenland Ice Sheet.



Ice mass loss from the Greenland Ice Sheet is raising global sea level by about 0.8 mm per year and is accelerating [1]. Basal lubrication by surface meltwater penetrating the 1000 m-thick ice sheet (Fig. 1) generates speedups during summer of 50–200% for the regions of the ablation zone experiencing sheet flow [2,3]. This seasonal acceleration has led to uncertainty in the dynamic sensitivity of the Greenland Ice Sheet mass balance to increased atmospheric temperatures. If surface melting translates directly to increased sliding, rising temperatures could generate a positive feedback to mass loss as faster flow causes the ice sheet to lower into warmer elevations [2,4]. On the other hand, if the subglacial hydrologic system of the ice sheet adapts to variable meltwater input, as observed on mountain glaciers, increased melt could generate a limited, or even decelerating, effect on seasonally averaged sliding and long-term dynamic response to warming climate [5,6]. Additionally, rapid drainage to the bed of water in lakes that form on the ice sheet surface can temporarily increase ice velocity by over an order of magnitude [7].

A better understanding of these processes is necessary for the next generation of ice sheet models to accurately predict the evolution of the Greenland Ice Sheet over the next century and its contribution to sea-level rise. In a modeling study where increases in ice flux were assumed to be proportional to increases in surface melt, the Greenland

Ice Sheet was projected to contribute to sea level rise at rates approximately 20% higher than when the effect is not included [4]. However, more recent work suggests the relationship between surface melting and sliding is not that simple [5,6] and, if so, such an approach may vastly overestimate mass loss from the ice sheet.

We investigated the seasonal and regional evolution of the melt-driven summer speedup of the Greenland Ice Sheet using velocity measured at nine global positioning system (GPS) stations across a study area spanning approximately 50 km of the western Greenland Ice Sheet (Fig. 2). Ice sheet velocity was compared to modeled surface melt and an inventory of lake drainages.

In the ablation zone of the ice sheet, there was a speedup of close to 40% during the summer, followed by a slight slowdown in late summer (Fig. 3), while acceleration was minimal close to the equilibrium line (stations 607–807). The regional speedup began within a few weeks of melt onset and persisted as long as air temperatures remained above freezing. Melt is well correlated with acceleration, but the magnitude of acceleration relative to melt decreases dramatically as the season progresses, indicating an evolution of the ability of the subglacial hydrologic system to accommodate the input of surface meltwater [6].

Subdaily velocity variations do not indicate a sustained season-long speedup, but rather a series of diurnal speedups, with nighttime velocities dropping near to winter values (Fig. 3). In fact, minimum daily velocity is somewhat higher than winter velocity initially, after the

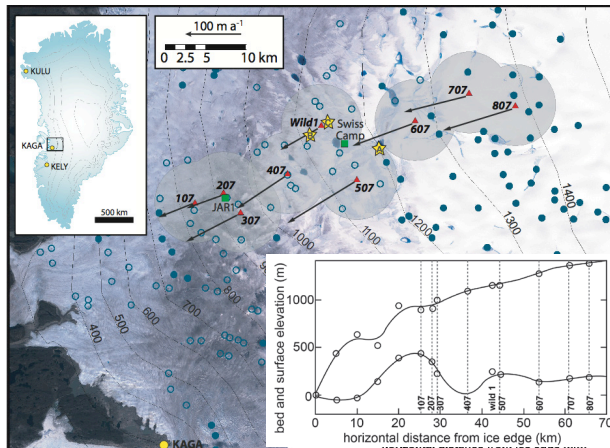
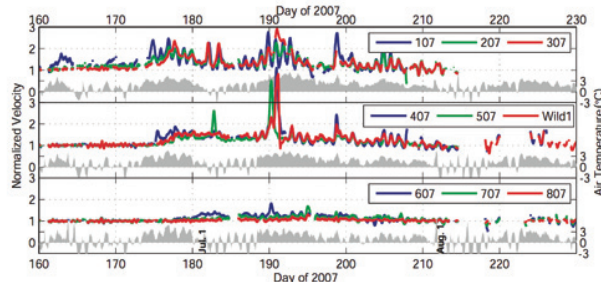


Fig. 2. Locations of GPS stations (red triangles), weather stations (green squares), and lakes (blue circles) shown on a LandSat image. Open/filled circles indicate lakes that drained/filled during the June 22–July 8, 2007 time period. Inset shows ice sheet surface and bed elevation along the GPS station flowline.

Fig. 3. Six-hour mean horizontal velocity (dark blue, green, and red lines) and hourly air temperature (gray) for GPS stations. Velocity has been normalized with respect to winter velocity.



seasonal speedup begins, but gradually lowers as the summer progresses (Fig. 4). However, the amplitude of daily speedup above the minimum velocity correlates strongly with daily melt production (Fig. 4). Thus, daily pulses of meltwater appear to drive daily acceleration, despite a clear seasonal evolution of the subglacial hydrologic system.

The dynamic response to meltwater input is similar to that observed on mountain glaciers. However, the ice in our study area is much thicker—about 1 km thick—which should cause creep closure within hours of efficient subglacial channels that develop beneath the

ice to convey water down-glacier. The fact that the subglacial hydrologic system evolves to increasingly greater efficiency as the summer progresses suggests that water pressures remain high enough to offset much of the overburden pressure of the ice, effectively making the ice sheet behave like thinner ice.

Over the summer we identified three lake drainage events in the region that locally increase daily velocity by two to three times winter velocity and result in significant surface uplift. However, less than half of the lakes greater than 0.5 km in diameter generated detectable acceleration; lake drainage can explain at most 5% of the total summer motion at any station, and it is therefore not an important component of the seasonal speedup.

Our observations support the ideas that rising air temperatures in Greenland may not translate directly into increased sliding at the seasonal scale [5,6] and that episodic pulses of water are key for generating enhanced sliding [5]. Daily pulses of meltwater appear to cause variations in daily sliding that are broadly consistent over space and time in our study area, but these daily increases in

velocity are superimposed on a nighttime velocity that generally decreases over the season, presumably as the subglacial hydrologic system becomes more efficient. Thus, accurately predicting future dynamics of the ice sheet in response to changes in surface melt may require knowledge of both melt generation and the state of the subglacial hydrologic system at high temporal resolution. Ongoing work involves introducing a realistic subglacial hydrology model that captures these effects in the ice sheet and Sea Ice Modeling (COSIM) project for modeling predictions of sea level rise from the Greenland Ice Sheet.

References

- Hoffman, M.J., G.A. Catania, T.A. Neumann, L.C. Andrews, and J.A. Rumrill, "Links between Acceleration, Melting, and Supraglacial Lake Drainage of the Western Greenland Ice Sheet," *J Geophys Res*, **116**, 16 (2011).
- [1] Velicogna, I., *Geophys Res Lett* **36**, L19503 (2009).
 - [2] Zwally, J. et al., *Science* **297**, 218 (2002).
 - [3] Joughin, I. et al., *Science* **320**, 781 (2008).
 - [4] Parizek, B.R., and R.B. Alley, *Quaternary Sci Rev* **23**, 1013 (2004).
 - [5] Schoof, C., *Nature* **468**, 803 (2010).
 - [6] Bartholomew, I. et al., *Nat Geosci* **3**, 408 (2010).
 - [7] Das, S. et al., *Science* **320**, 778 (2008).

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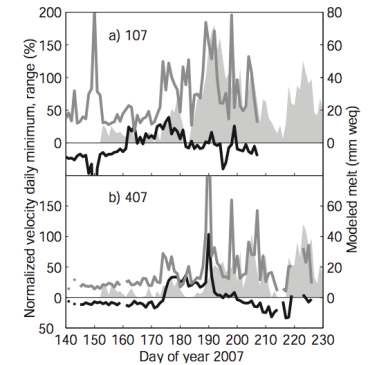


Fig. 4. Minimum daily velocity (black) and difference between maximum and minimum daily velocity (dark gray) for stations a) 107, and b) 407. Modeled daily melt is shown with light gray shading.